A Fatigue Model for Fiber-Reinforced Polymeric Composites in Civil Engineering Applications

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A fatigue model based on cumulative damage is developed for predicting the fatigue life of fiber-reinforced polymeric composites in offshore applications. This model incorporates applied maximum stress, stress amplitude, loading frequency, residual tensile modulus, and material constants as parameters. The model is verified with experimental fatigue data of a glass fiber/vinyl ester composite in various environments. While the specimens are exposed to air, fresh water, and sea water at 30°C, they are subjected to tension/tension stress at four levels of applied maximum tensile stress in each of two frequencies. Both the residual mechanical properties at specified loading cycles and the number of cycles at which the specimens fail are measured. These data are used to determine the model constants.

The Fatigue Model. The fatigue damage per cyclic loading, residual modulus in term of partial damage, and fatigue life of fiber-reinforced polymeric composites are described as functions of applied maximum stress, stress amplitude, loading frequency, state of damage, and materials constants as the following:

$$\frac{dD}{dN} = (C_1+\frac{C_2}{f})\frac{(\sigma_{max}^2(1-R))^m}{(1-D)^n} \quad (1)$$

$$\frac{1}{n+1}-\frac{(1-D)^{n+1}}{n+1} = (C_1+\frac{C_2}{f})(\sigma_{max}^2(1-R))^m N \quad (2)$$

$$\frac{1}{n+1} = (C_1+\frac{C_2}{f})(\sigma_{max}^2(1-R))^m N_f \quad (3)$$

where,

C, m, and n are the material constants which are determined from experimental data.

σ_{max} is the maximum stress, or the normalized maximum stress to ultimate strength,

R is the ratio of minimum to maximum stress,

D is the state of damage defined as:

$D = 1 - E/E_0$ and *E* and *Eo* are the residual and initial moduli, respectively,

N is the numbers of loading cycles before failure, and

N_f is the numbers of loading cycles at failure.

Experimental Procedure. The specimens used in these experiments are obtained from a vinyl ester /E-glass fiber composite. The flat laminate composite is a cross-ply material which consists of unidirectional roving and a random mat of continuous fibers in the off-axis. The composite is the same material used in the construction of the Tom Creek a.11-composite bridge in Blacksburg, Virgina, in July of 1997. The specimens are cut into a rectangular shape of 200 mm long, 25 mm wide, and 32 mm thick. The edges of the specimens are then coated with epoxy to prevent the sorption of water into the composite from the edges.

Fatigue experiments are conducted in a tensiontension mode with an R value of 0.1. Maximum loads applied range from 35% to 65% of ultimate tensile strength, and frequencies are set at 2 Hz and 10 Hz. All experiments are conducted at room temperature(30°C) on a servo-hydraulic fatigue test frame that has a tension-compression load capacity of 100 kN. The specimens used to simulate fresh water and salt water environments are attained by immersing in charcol filtered tap water where chlorine and minerals are removed and in a 3.5% NaCl solution at 65°C for 506 and 451 hours, respectively, to reach 95% of saturation. Before fatigue loading, the ultimate tensile strength, modulus, and Poisson's ratio are measured in dry air(45% relative humidity at 30°C), fresh water, and salt water environments. The following table presents the results of these measurements.

Table 1. Mechanical Properties of E-glass/Vinyl Ester Composite

	Dry air	Fresh Water	Salt Water
Ult. stress(MPa)	212	158	144
Modulus(GPa)	15.55	13.26	13.85
Poisson's Ratio	0.31	0.31	0.31

This table shows a 25% and 32% reduction of ultimate strength in fresh water and salt water conditions, respectively, as compared to the dry air environment. The corresponding reduction in tensile modulus, are 15% and 11%, respectively.

Two sets of fatigue experiments are carried out. In the first set, the experiment is stopped at selected numbers of cycles; the specimens are then removed from the testing machine and the residual strength, tensile modulus, and Poisson's ratio are measured. These results provide the partial damages that occur at given numbers of loading cycles. These damages are used to determine the material constant n in Eq. 2. In the second set, the fatigue experiments are carried out at selected loadings until the specimens fail. The applied load and the number of cycles at failure are recorded. These data are used to establish the S-N curves and to verify the fatigue model (Eq. 3). The data are also employed to determine the value of m. Experimental data on two frequencies are used to determine C1 and *C2.*

Figure 1. Fatigue at 10 Hz in Dry Air, Fresh Water, and Salt Water.

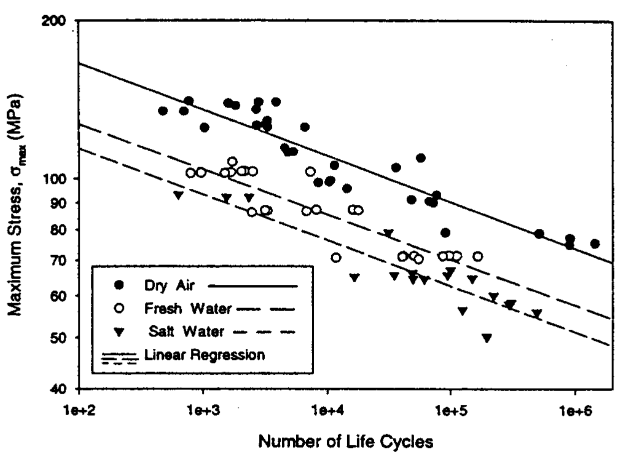
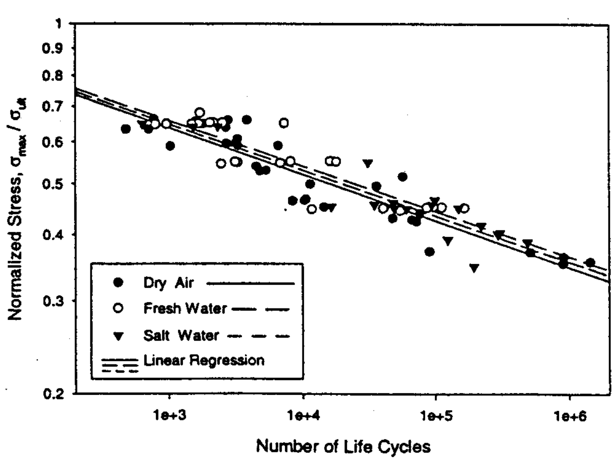


Figure 2. The Closeness of Normalized S-N Curves in Three Environments.



<u>Model Verification.</u> In Figure 1, the maximum stress is plotted against the number of cycles at failure for fatigue experiments in three different environments (dry air, fresh water, and salt water). When we take a logarithm on both sides of Eq. 3, the experimental data fit well with a linear relationship between log(stress) and log(N), that substantiates the validity of the fatigue model. It is interesting to note that there is little difference in the slopes of the linear-fit lines of the S-N data for the three environments, suggesting that the fatigue failure mechanism does not change with the exposure environment. This figure also reveals that, under the same applied load, the fatigue life of the composite in air is greater than that in fresh water or salt water. The difference in fatigue lives between fresh water and salt water environments is small.

Figure 2 shows the normalized S-N curve, the maximum stress to respective ultimate strength in the environment versus the number of cycles at failure. The closeness of the S-N curves derived from separate fatigue experimental data at 10 Hz in dry air, fresh water, and salt water environments suggests that a single fatigue model(Eq. 3) can be used can be used to predict the fatigue life of a vinyl ester/E-glass fiber composite exposed to air, fresh water or salt water.

Our experimental data for two frequencies, 2 Hz and 10 Hz, indicate that frequency has little effect on m or *n.* Using the experimental data to determine the model constants, we have obtained the following equation for S-N curve of a glass fiber reinforced vinyl ester composite exposed to three environments:

$$\sigma_{max}^{11.40} N_f = \frac{13.11}{1+\frac{8}{f}} \tag{4}$$

where σ_{max} is the normalized stress to static ulti mate strength $(\ |\sigma_{max}| \leq 1)$.

The residual modulus for a given maximum applied load after *N* loading cycles may be predicted as:

$$\frac{E}{E_0} = (1 - \frac{\sigma_{max}^{11.40} N(1+\frac{8}{f})}{13.11})^{\frac{1}{n+1}} \tag{5}$$

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